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Human comfort, urban climate change and energy use: Assessing adaptation options for the rapidly growing tropical mega-cities

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ABSTRACT: The rapid urban growth in the tropics, while being a problem in itself, leads to urban climate changes which pose additional strains on urban energy supply and human comfort. Primary causes for such urban climate changes are amenable to design interventions: urban geometry (limited sky view), thermal properties of building surfaces, anthropogenic heat and air pollution. The net effect of urban climate changes super-imposed on regional changes in tropical cities is the increasing need for building cooling energy. The urban thermal stress on the already stressful tropical climate is making it nearly intolerable. This paper reports the thermal comfort and urban energy implications of a large-scale housing development in urban Sri Lanka, with the aid of building- and neighbourhood-scale model simulations. A cool thermal environment by built-form and layout manipulation is promoted as the preferred adaptation mechanism for high-density tropical cities. Building energy and thermal comfort implications are also explored.

Keywords: Thermal comfort, urban heat island, tropical climate, urban morphology, heat island mitigation

1. INTRODUCTION

The pursuit of energy-efficient architecture and optimum human comfort cannot ignore the changing climatic conditions in the outdoors. This is especially so in tropical regions where the generally open nature of buildings blur the boundary between the “inside” and “out.” A design option that treats the “outdoor” as an extension of the “indoor” is not only possible but mandatory in the tropics where the year-round “livability” of the outdoor is high [1].

At the same time, the changing urban climate and high population densities bring about their own feedback mechanisms that are making passive design options less successful in the rapidly urbanizing tropical regions. As the standard of living of tropical dwellers increases, the difficulties in achieving passive thermal comfort are likely to be confounded by the growing urban heat island problem. Such a scenario will lead to large increases in building energy use on account of the already stressful tropical climate. It is therefore essential that architects and urban designers explore energy-efficient design options at the neighbourhood and urban scale .that help urban dwellers adapt to urban climate change without compromising thermal comfort.

2. BACKGROUND

2.1 The urban heat island effect

The Urban Heat Island (UHI) a phenomenon scientifically recorded for the first time in 1837 by Luke Howard in London [2] has been observed in all climate regions of the world. Contemporary research work in UHI was pioneered by Oke [3][4]. Since the early work of Oke [5], there is mounting evidence that urban geometry and thermal properties of surface material in urban areas (i.e. land use) are the major causes of UHIs [4], [6]. The urban geometry is characterized by several methods: (i) by the canyon (a three-dimensional space bounded by a street and the buildings that abut it) geometries, measured in terms of the building height (H) to street width (W) ratio; (ii) the Sky View Factor (SVF), which signifies the fraction of sky dome visible from a given outdoor point; and, (iii) a “compactness index” [7], which is defined as the ratio of building surface area (excluding the plan area) to the surface area of a cube which has the same volume as the building. Todhunter [8] argued that for micro-scale phenomena the urban geometry is more important but at the meso-scale both the geometry and surface thermal characteristics play an equal role.

In addition to urban geometry and surface thermal properties, the following factors also contribute to urban microclimate modifications: (i) Anthropogenic heat (heat waste from combustion and metabolism); (ii) Urban ‘greenhouse’ effect (increased incoming long-wave radiation from polluted urban atmosphere); (iii) Evapotranspiration loss (reduction of green areas in cities lead to more sensible than latent heat transfer); and (iv) wind shelter (reduced ability of wind to carry heat either as sensible or latent turbulent heat flux [8], [9], [10], [11]. Oke [9] argued that non-geometrical effects such as heat capacity and anthropogenic heat release may be linked to urban geometries, since high density buildings are, by definition, associated with extensive land use (more artificial surfaces) and intense human activity (thus, higher amounts of waste heat).

The link between urban layout and daytime air temperature in warm climates is well documented. In the hot humid summer of Dhaka, Bangladesh, Ahmed [12] found that the maximum air temperature decreased with increased H/W ratio. Similarly, in the hot, dry, climate of Fez, Morocco, Johansson [13] found that a very deep street canyon had a considerably lower air temperature than a shallow street canyon. In hot, humid Colombo, Sri Lanka, Emmanuel & Johansson [14] found intra-urban differences in maximum daily temperatures of up to 7 K between sites of different urban geometries.

2.2 UHI and Human well-being

The human dimension of UHI is increasingly being documented. Studies in Pune, India [15] have shown the increasing discomfort expressed in terms of the temperature-humidity index THI (which is also known as a discomfort index that is used to determine the effects of summer conditions on human comfort combining the temperature and humidity). Studies in Colombo, Sri Lanka [13], [16] show the deteriorating outdoor conditions in terms of the Relative Strain Index [17] and Physiologically Equivalent Temperature PET [18], [19], [20]. The relative strain index is the ratio of the amount of sweat evaporation needed for comfort to the amount of evaporation possible in the given ambient atmospheric conditions. PET is a thermal index defined as the air temperature at which, in a typical indoor setting (without wind and solar radiation), the heat budget of the human body is balanced with the same core and skin temperature as under the complex outdoor conditions to be assessed. Similar findings have been reported from Dhaka, Bangladesh [21]; Cambridge, England [22] and Sydney, Australia [23].

There has also been a change of lifestyle among urban dwellers in recent times, especially in the medium and high-income groups, who spend more time indoors than outdoors [21]. In the face of increasing discomfort in the outdoors, one could expect more human activities to occur indoors, which might necessitate greater use of air-conditioning which in turn will exacerbate outdoor temperatures as the excess heat is emitted to the urban air [24], [25]. Another consequence is the increase of water usage [26]. This is especially problematic in hot, dry areas where water resources are scarce. Furthermore, UHIs add to the urban mortality/morbidity concerns [27], [28]. While heat waves in general are major health hazards, urban areas worsen these problems, even in temperate cities during hot summers.

2.3 Outdoor thermal comfort

Attempts toward quantifying the urban bio-climate are relatively new, with early efforts traced only to 1970s; for a review, see [29]. Although these attempts have helped modify existing indoor climate models in the context of outdoor environments, some new indices specifically suited for outdoor applications have also been developed recently, the most prominent among them being the PET.

ASHRAE's Standard 55 [30] specifies human comfort in terms of 6 variables: air temperature, air velocity, relative humidity, Mean Radiant Temperature (MRT), clothing insulation and metabolic rate (i.e. human activity). In an indoor situation it may be reasonable to assume the air temperature to be equal to MRT, but this is an oversimplification in the urban context, due to a number of reasons ranging from psychological to physiological factors [31]. Large differences exist between these temperatures in the outdoors, particularly in areas with direct solar radiation; for example, adjacent areas exposed to direct sunlight and shade have different MRTs although the air temperature is essentially the same. Thus, MRT assumes greater importance in estimating outdoor thermal comfort.

The MRT is often calculated as the weighted average temperature of surrounding surfaces. It is more complicated to calculate the MRT in an outdoor urban environment than indoor due to factors such as the exposure to solar radiation, the varying shapes and positions of buildings and the presence of objects such as trees, etc. Nevertheless, surface temperatures of dominant surfaces are a good proxy to MRT in urban areas.

2.4 UHI mitigation

The conventional approach to UHI mitigation is primarily differentiated by the scale of intervention. At the local (neighbourhood) and micro scales (several buildings to entire streets), mitigation strategies have mainly focused on three aspects: albedo enhancement [32], [33]; increased vegetation cover [34], [35], [36] and "cool roof" strategies [37], [38], [39]. The aim of these efforts is to reduce the negative feedback of urbanization upon air temperature and space cooling of buildings. Other mitigation strategies at neighbourhood scale include ventilation enhancement, both sea-breezes [40], [41] and estuarine breezes [42]. Within the urban canopy layer, particularly at street level (pedestrian height) the focus has been on shade enhancement ("shadow umbrella" [16].

3. METHOD

In this paper we present the results of building- and neighbourhood-scale climate and energy simulations of a large-scale housing development project in a rapidly urbanizing region in Sri Lanka. The aim is to estimate the outdoor comfort/climate effects of neighbourhood design strategies and to explore the indoor thermal comfort and cooling energy implications of such strategies. The premise is that tropical neighbourhood design strategies need to be mindful of the UHI effect and the mitigation of UHI is critical to improve indoor comfort and energy efficiency. The study aims to

i. Estimate the outdoor climate (air temperature) that result from the different neighbourhood layout options;
ii. Propose design strategies to improve outdoor conditions by way of street orientation and building layout;

iii. Estimate the indoor thermal comfort and energy implications of outdoor design strategies

The present work utilizes numerical modelling to estimate the air temperature, cooling load and outdoor thermal comfort effects of the above strategies in a tropical urban location (Colombo, Sri Lanka, Latitude = 6.9^{o}N; Longitude = 79.9^{o}E; 7m ASL). The existing built fabric of the location is shown in Figure 1.

Figure 1: Neighbourhood layout plan of the case study area

Having calculated the air temperature and thermal comfort implications of UHI mitigation options, building energy use implications are explored with the help of a parametric building energy model.

3.2 Numerical modelling

In the field of urban climate analysis and mitigation, numerical models have the obvious advantage over field measurements on account of their controllability as well as time and resource frugality. The non-linearity of the urban climate problem lends itself to numerical model-based analysis and is therefore increasingly popular in urban climatology [43].

Urban microclimate models vary widely, based on their physical basis and spatial/temporal resolution. Ali-Toudert & Mayer [44] provide a detailed critique of the more popular models at the micro-scale with fine temporal resolutions. They inferred that ENVI-met [45] is perhaps the only micro-scale computational fluid dynamic model that is capable of analyzing the thermal comfort regime within the street canyon at fine resolutions (down to 0.5m x 0.5m). We have therefore selected ENVI-met (version 3, http://www.envi-met.com) as the numerical model to analyze the effect of neighbourhood layout. ENVI-met is a three-dimensional non-hydrostatic model for the simulation of surface-plant-air interactions especially within the urban canopy layer. It is designed for micro-scale with a typical horizontal resolution from 0.5 to 10 m and a typical time frame of 24 to 48 hours with a time step of 10 sec at maximum. This resolution allows the investigation of small-scale interactions between individual buildings, surfaces and plants [46].

Input data required to initiate ENVI-met simulations are:

i. Wind speed and direction at 10m above ground;
ii. Roughness length (Zo);
iii. Initial temperature of atmosphere;
iv. Initial temperature and humidity of the soil
v. Specific humidity at 2500m;
vi. Relative humidity at 2m.

The model calculation includes:

i. Shortwave and long-wave radiation fluxes with respect to shading, reflection and re-radiation from building systems and the vegetation;
ii. Transpiration, evaporation and sensible heat flux from the vegetation into the air including full simulation of all plant physical parameters (e.g. photosynthesis rate);
iii. Ground surface and wall temperature for each grid point and wall;
iv. Water- and heat-exchange inside the soil system;
v. Calculation of bio-meteorological parameters such as Mean Radiant Temperature or Predicted Mean Vote (PMV) [47].

A shortcoming with ENVI-met is that buildings, which are modelled as blocks where width and length are multiples of grid cells, have no thermal mass and have constant indoor temperature. Moreover, albedo and thermal transmission (U-value) for walls and roofs are the same for all buildings.

3.2 Building climate simulation

The estimation of building climate (i.e. indoor thermal comfort and cooling load) employed a parametric building energy simulation program called DEROB-LTH [48]. DEROB-LTH is capable of simulating the indoor thermal comfort and building cooling/heating energy needs (if the building is to be air conditioned or heated respectively). It uses ray-tracing technique to calculate the effect of building parameters such as thermal properties of building materials, orientation, window size, room size, shading devices and insulation upon indoor climate. The climatic inputs needed for simulation are:

i. Outdoor average daily maximum and minimum air temperature;
ii. Outdoor average daily maximum and minimum relative humidity;
iii. Average daily cloud cover (or total global radiation)
iv. Average monthly rainfall.

The program calculates the indoor thermal comfort in terms of Fanger's [47] PMV and is also capable of calculating the cooling (or heating as the case may be) energy needed to maintain a pre-determined level of indoor thermal comfort.

3.3 Simulation cases

i. Neighborhood model

Figure 2 shows a typical layout option for the housing scheme (the "base case"). Street canyon is oriented northeast-southwest while houses are coupled and staggered (i.e. front and backyard width vary alternatively). Property lines too, are staggered.

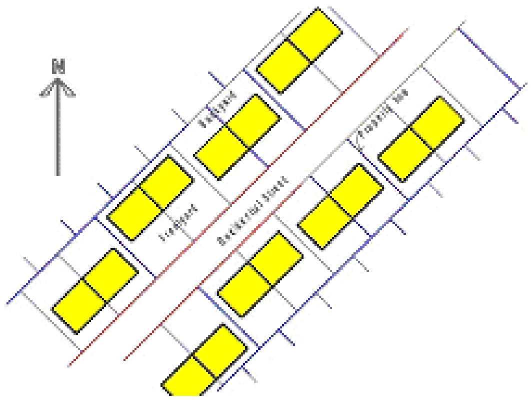

Figure 2: Typical schematic layout of dwelling units

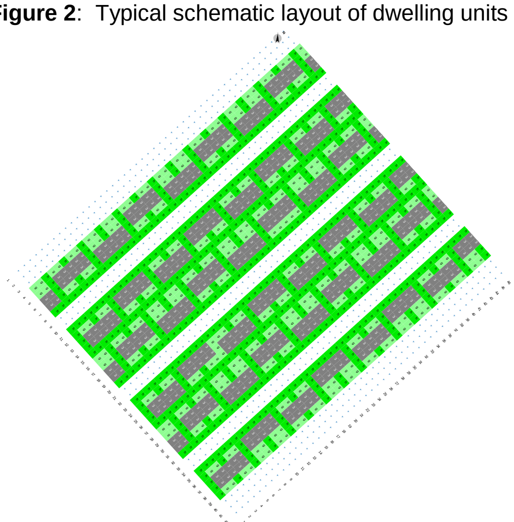

Figure 3: ENVI-met representation of a typical dwelling layout

In representing the above layout for simulation purposes, certain non-thermal features have to be adjusted and a peculiar limitation of the current version of the software is the need to represent the domain in a grid-format. We selected a 5m x 5m grid on the X- and Y-axis and 3m grid on the vertical axis (see Figure 3). Street itself was asphalt paved (in the base case) and buildings are assumed to be made of brick wall (cement : sand plastered) and roofed with clay tiles. Property lines are demarcated by live hedge. Street side vegetation includes 10m diameter evergreen trees on every other plot.

ENVI-met simulations investigated the following cases in addition to the base case as described above:

i. Street orientation – Northeast-Southwest
ii. Street orientation – North-South
iii. Street orientation – Northwest-Southeast
iv. Staggered building line
v. More tree cover (at least one tree in every front yard)
vi. Unpaved ("Green") street cover.

ii. Building model

The building-level simulation in DEROB-LTH used the following parameters to represent the existing case (the "Base Case"). Plans of two options studied here are presented in Figure 4. DEROB-LTH representation of the housing options is shown in Figure 5. The following conditions were assumed:

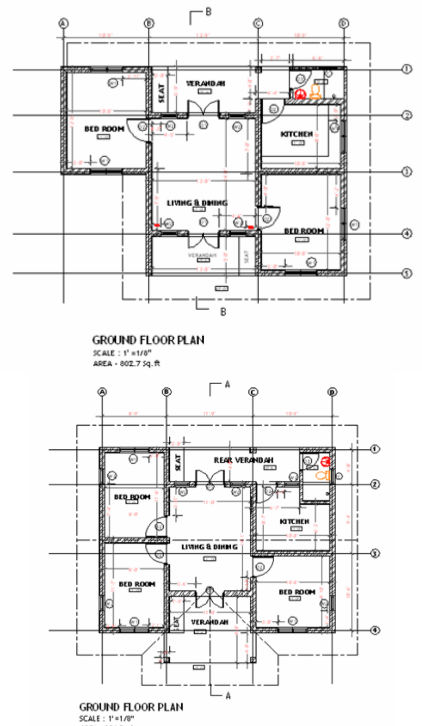

Figure 4: Plan of two housing options studied – Option 'A' (top) & Option 'B' (bottom)

i. 9m wide street, lined with 150m^2 plots on both sides, each plot surrounded by 1m high live hedge;
ii. Each plot has a 75m^2 single-story house with two bedrooms, a toilet, a kitchen and a living/ dining area. Houses are laid on a staggered form, with alternating houses having the legal minimum rear space (2.5m). Every other house has a larger rear space (and thus smaller front yard). For reasons of simplicity of the computer model, the internal partitions of the house are ignored;
iii. The house is constructed of 225mm thick brick walls, plastered both sides (outside rough plastered and dark coloured inside lime plastered and white coloured); clay tile roof on timber frame with flat asbestos sheet ceiling; 6mm thick, single glazed windows on wood frames; tiled floor on 100mm mass concrete;
iv. All windows are shaded by 1m wide horizontal shading devices;
v. The house is considered air-conditioned for the purpose of calculating the cooling load. The rate of infiltration is assumed to be 0.5 Air Change per Hour (ACH).

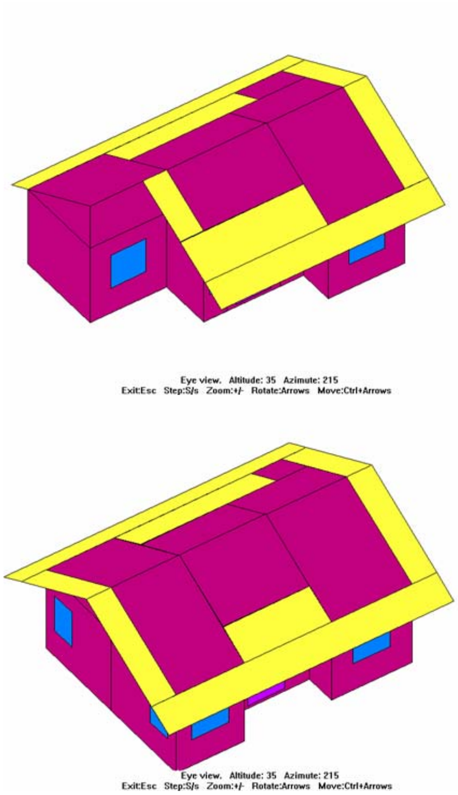

Figure 5: Isometric view of the base case – Option 'A' (top) & Option 'B' (bottom)

Internal temperature of the house is set lower at night and slightly higher during the day. The house is assumed to have four occupants.

In addition to the existing case, the following options were studied:

i. Main entrance facing East (90^{o} rotation);
ii. Asbestos roof;
iii. Tile roof with polystyrene insulation;
iv. White painted roof cover.

The first option was studied to estimate the effect of layout (orientation), while the other three options estimate the effect of various roofing options. In a tropical context, roof is the most important controller of indoor comfort; the high solar angles make walls less important from the solar point of view [16].

4. RESULTS AND ANALYSIS

Figures 6 & 7 show ENVI-met simulated surface temperatures on the street- and rear-side of the houses for three street orientations (Northeast-Southwest, North-South and Northwest-Southeast), two options for building arrangements (staggered), a landscape street ("Green case") and one option for street paving ("green" paving instead of standard asphalt-paved road). It is clear that street orientation contributes to the outdoor temperature (and, by inference, to the thermal comfort). A strategy to plant trees in the front-yards of lots will also be beneficial. The effect of non-asphalted street is minimal.

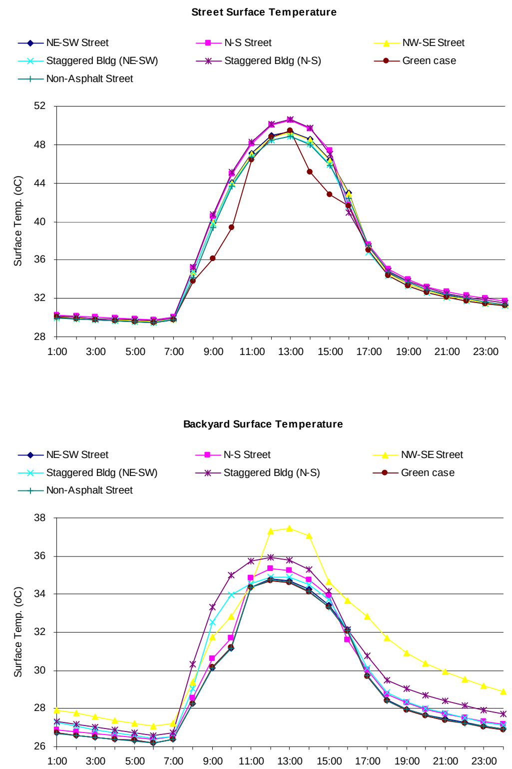

Figure 6: Surface temperatures on the street-side (above) and rear-side (below) of dwellings

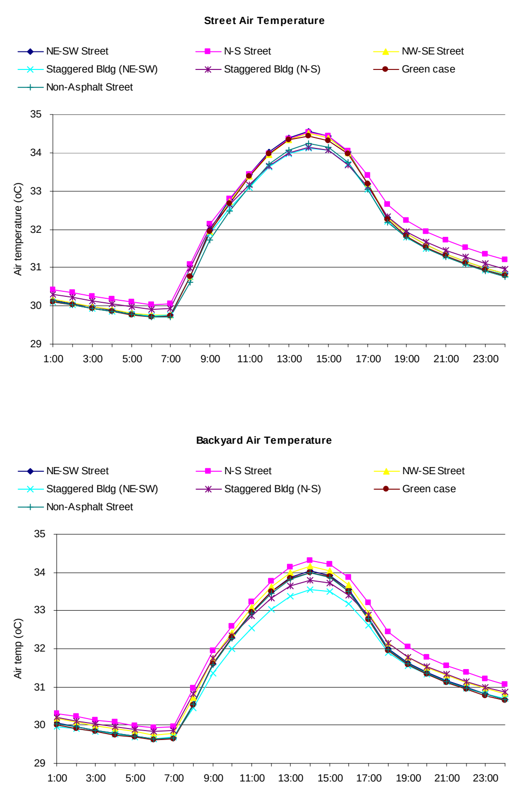

Fig 7: Air temperature variations – Street side (above) & Backyard (below)

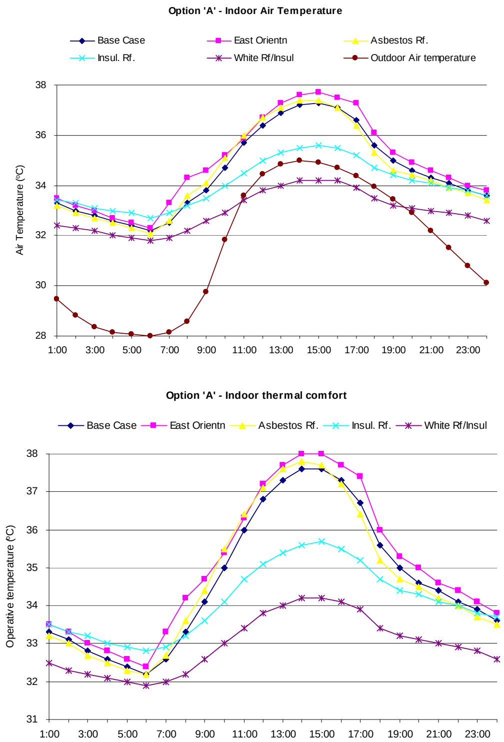

Figure 8: Indoor conditions in House Option ‘A’ – air temperature (above) and operative temperature (below)

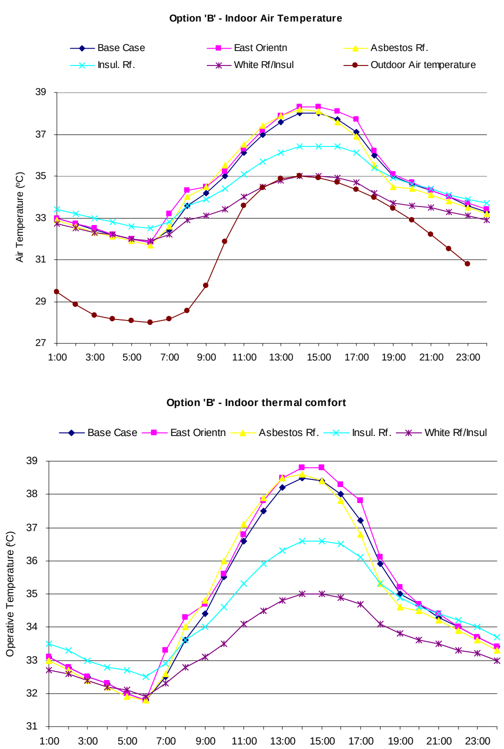

Figure 9: Indoor conditions in House Option ‘B’ – air temperature (above) and operative temperature (below)

The indoor thermal conditions are presented in Figure 8 (Option ‘A’) and Figure 9 (Option ‘B’). These results were obtained from DEROB-LTH simulations.

The best indoor comfort option is to paint the roof white and use roof insulation. The second best option would be to use roof insulation alone. Up to 3 deg. C reduction in indoor air temperature is possible with white roof/roof insulation combination. Nearly 2 deg. C reduction could be achieved by insulating the roof. Such reductions are remarkable, considering the fairly constant and warm outdoor conditions prevailing in tropical Sri Lanka. In terms of layout, East-West orientation (i.e. main entrance facing east) is seen as the worst option.

Table 1 shows the potential cooling load reductions that could be achieved by manipulating the roof design. These are worked out on the hypothetical basis of air conditioning the house. This was done as a thought experiment to quantify the potential cooling effect of different roof design strategies.

Table 1: Potential cooling load reductions due to different roofing strategies

	Cooling Load (kWh)	Saving over Base case
Option 'A'		
Base Case	26.32	0.0%
Insulated Roof	23.83	9.5%
White Roof w/ Insulation	21.74	17.4%
Option 'B'		
Base Case	29.26	0.0%
Insulated Roof	26.88	8.1%
White Roof w/ Insulation	24.57	16.0%

It appears that white roof with insulation will afford the most savings in terms of cooling load, while roof insulation by itself contribute to up to 9.5% reduction in cooling load. Roof insulation by itself has the potential to reduce the cooling load by approx. 2.5 kWh per day. This will be equivalent to an annual energy saving of 1,500x 365 x 2.5 kWh (1.3 GWh) for the entire housing scheme. In the context of rising electricity tariffs, such savings will be economically significant at the national scale.

5. DESIGN STRATEGIES

From the above, we could surmise the following at the urban design (settlement-level) and the building design (individual units) scales:

5.1 Settlement scale

i. Northeast – Southwest street orientation is better, especially when the houses are staggered. This arrangement improves the wind turbulence
ii. North-South street orientation did not fare as well as (i) above, due to its poor orientation to prevailing wind
iii. Encourage at least one medium-size tree (crown dia. = 10m) in each front-yard

iv. Wind speeds around buildings were similar even when buildings were not aligned equidistance from street line
v. Encourage backyards to be as green as practical

5.2 Building strategies

i. Preferred orientation: Main entrance facing South
ii. Differences in energy saving between different housing options is minimal
iii. Preferred roof cover: Tile
iv. Roof insulation will reduce 8.0-9.5% of the cooling load
v. Roof strategy: at least 20mm roof insulation
vi. White roof will reduce an additional 8% of the cooling load.

6. CONCLUSION

The present study shows that substantial improvement in thermal comfort is possible by manipulating the settlement geometry and by carefully controlling individual dwelling design. A staggered arrangement of buildings, coupled with northeast-southwest street orientation appears to lead to the most comfortable outdoor conditions in the urban context of Sri Lanka. Other streets that are not thus oriented could benefit from the promotion of street level tree planting. Moderate sized evergreens will be sufficient for this purpose.

At the individual dwelling-level, thermal comfort could be augmented by careful roof design. At the minimum, good roof insulation is needed. If it could be “aesthetically managed,” a white (or at least light coloured) roof design could further augment the indoor comfort.

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